VALIDATION TESTING OF A NEW DUAL HEAT PULSE, DUAL LAOYER THERMAL PROTECTION SYSTEM APPLICABLE TO HUMAN MARS ENTRY, DESCENT AND LANDING

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ABSTRACT

In NASA's quest to find a system capable of delivering 40 metric ton payloads to the surface of Mars, one proposed mission scenario employs a 10 x 29 meter mid lift-over-drag (L/D) vehicle with a dual heat pulse capable thermal protection system (TPS) that achieves orbit via aerocapture, cools down there, and then enters, descends and lands. This paper discusses the simulated dual heat pulse thermal testing conducted in the Ames arcjet complex of a dual layer, phenolic impregnated carbon ablator (PICA) atop a LI-900 (Shuttle insulating tile) TPS attached with large honeycomb (~ 5 cm), proposed for this mission scenario. Test results and recommendations for future work on the maturation of the dual heat pulse TPS technology are provided.

1. INTRODUCTION

During the past several years, NASA has been conducting studies [1,2] of human missions to Mars and advanced systems that can deliver 40 metric tons of payload to the surface. Figure 1 is an artist's drawing of a mid L/D vehicle of dimensions 10 x 29 meters that has been studied by NASA's Entry Descent and Landing - System Analysis (EDL-SA) Project. This vehicle would be aerocaptured at Mars, stay in orbit for up to several months, and then enter the atmosphere followed by the descent and landing phase.

This scenario involves two heat pulses, one for aerocapture and the second for entry. During the first study [1], a new dual-layer thermal protection system (TPS) concept was proposed to achieve the mass efficiency necessary to enable and satisfy the mass requirement of the mission. This dual-layer TPS concept is capable of withstanding dual heating pulses. During the same time frame, a new TPS manufacturing scheme using a large (~ 5 cm) honeycomb attachment was also developed [3,4] offering manufacturing ease as well as the capability to integrate multiple TPS materials in the heat shield for large entry capsules. The composition and thickness of the TPS material blocks contained in the honeycomb could be tailored to address the local heating environments, which vary widely across the heat shield. This manufacturing approach for the dual layer TPS for the 10 x 29 meter mid L/D vehicle was adopted for the system analysis [2] since previous arc jet testing by the Orion TPS Advanced Development Project (ADP) [3,4] showed it to be viable for singular heating rates at levels appropriate for both the aerocapture and entry heat pulses of interest for the mid L/D vehicle. System studies [2] show that the PICA atop LI-900 (Shuttle tile) TPS attached with the large honeycomb would be 23 percent lighter than one employing a PICA tile system attached with Shuttle Strain Insulation Pad (SIP) and Room Temperature Vulcanized (RTV) - filled gaps similar to that which will be flown on the Mars Science Laboratory (MSL).

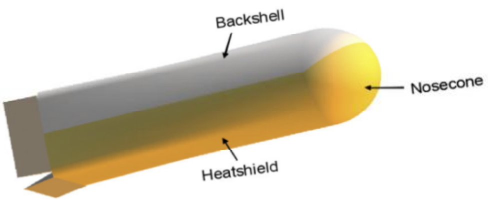

Fig. 1. Mid L/D 10 x 29 meter vehicle that would deliver 40 mt to the surface of Mars. Flight direction is from left to right. The lower (windward) surface would be covered with the dual heat pulse, PICA atop LI-900 dual layer TPS.

Fig. 2 (a) illustrates the large honeycomb TPS manufacturing concept and post arc jet test articles where the material filling the honeycomb was PICA only. The PICA is bonded into the honeycomb with RTV, a bonding and gap-filling adhesive used on the

Shuttle and MSL. The test conditions for Fig. 2 (b) clearly indicate that the thermal performance of PICA

(a) (b) (c)

Fig. 2. PICA in large honeycomb (~ 5 cm): (a) Demonstration curved panel; (b) post tested stagnation iso-q model with PICA after exposure to 620 W/cm^2 for 30 seconds; (c) post tested swept cylinder model after exposure at 140 W/cm^2 for 25 seconds [4]

in honeycomb is viable at entry environments exceeding the peak heating rate values predicted for the aerocapture portion of the mid L/D vehicle, shown in Fig. 3 a. The same conclusion can be made from Fig. 2 (c) for the lower, second, peak entry heating pulse also shown in Fig. 3a. At both the aerocapture and entry peak heating conditions, the honeycomb and PICA recede at approximately the same rate, and “fencing” of the honeycomb does not seem to be an issue.

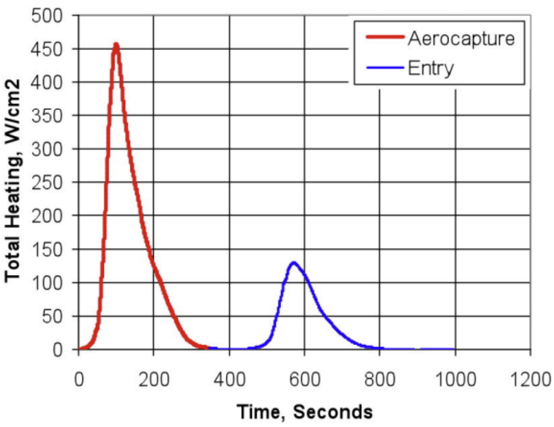

Fig. 3a Mid L/D Aeroshell Dual Pulse Peak Surface Heating History and (b) Arcjet heating profile simulating the dual heat pulse environments.

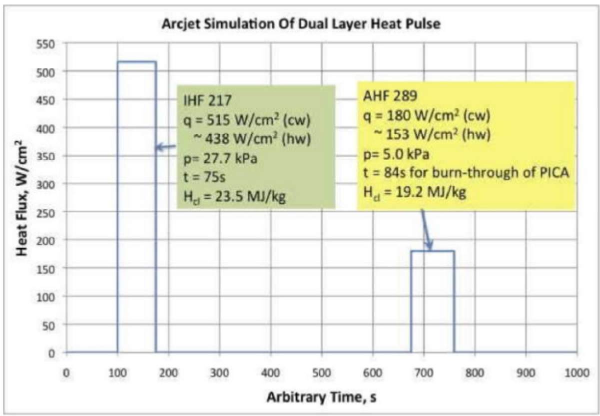

Fig. 3b Arcjet heating profile simulating the dual heat pulse environments

2. DUAL PULSE, DUAL LAYER PICA ATOP LI-900 VIABILITY TESTING

Viability testing of the dual heat pulse, dual layer concept was performed by simulating the aerocapture, on-orbit cool-off, and subsequent entry in the Ames arc jet complex. First, the aerocapture was simulated in the Ames Interactive Heating Facility (IHF) at 438 W/cm^2 (hot wall) and 28kPa pressure for 75 seconds. This constant heating condition shown in Fig 3 (b) simulated the aerocapture heat pulse shown by the red curve in Fig. 3 (a). The same, charred model was then stored for several months at room temperature with a desiccant to simulate cool down in Mars orbit. Lastly, the model was exposed to 153 W/cm^2 (hot wall) and 5kPa for 109 seconds in the Ames Aerodynamic Heating Facility (AHF) to simulate the out-of-orbit entry heat pulse and understand any failure modes at burn-through into the LI-900. The second, constant heat pulse in the AHF simulates the entry heating shown by the blue curve in Fig. 3 (a). Fig. 4 below depicts the iso-q, dual layer test article design. The model was designed with an outside ablative layer 1.9 cm thick atop a 1.9 cm thick layer of LI-900. Five models were made; two had no bonding between the iso-q faces of the PICA and the LI-900 and three had a very thin layer (~ 0.02 mm) of RTV at the boundary of the ablator and the insulator. Each model had the LI-900 press fitted against the inner face of the PICA to ensure thermal contact. The flow in the arc jet test impinges on the curved surface of the test article (left to right) and the shape of the model tends to make the surface heating constant (iso-q).

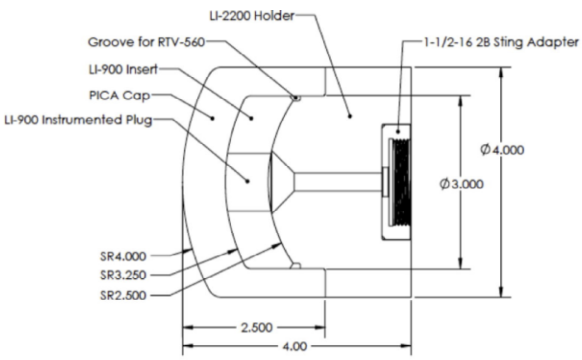

Fig. 4. Iso-q model. Dimensions in inches

Two IHF tests were run. The first was run for 75 seconds duration corresponding to the aerocapture pulse. It was predicted by the ablative analysis tool FIAT [5] that the test would leave 0.63 cm of charred PICA. The actual measured value was 0.61 +/- 0.025 cm. The second test allowed the model to remain in the stream until the PICA receded to the LI-900 interface in order to understand any failure mechanisms during burn-through. Burn-through was predicted by FIAT to occur at 108 seconds while the actual burn through was measured at 107 seconds. Fig. 5 (a) shows the first post-tested model with 0.61 cm of charred PICA remaining.

Fig. 5a. Post tested model at the IHF run condition - Tested for 75 seconds in the IHF

Fig. 5b. Burned-through model after an overtest of 107 seconds at the IHF condition showing a failure mode of the dual layer PICA atop LI-900 TPS concept

Fig. 5 (b) shows the burned-through model that was removed from the stream after 107 seconds. As can be seen, the LI-900 slumped (shrinking occurred). This is considered to be a failure mode and shows that, for the flight design, there must be sufficient PICA remaining after the first pulse to prevent burn-through of the PICA during entry from orbit, as discussed in the analysis section above.

A dual layer model tested at the first pulse IHF condition with RTV bonding between the PICA and the LI-900 was stored for several months and then tested for a second heating pulse in the AHF arc jet. The second heat pulse level was 153 W/cm^2 (hot wall) and 5KPa, simulating the heating during out-of-orbit entry. The test time of 84 sec. was selected based on anticipated PICA burn through. This test time is far in excess of the heat-load for the second pulse representing entry from orbit for the Mars mission profile. The objective was to go far beyond the performance characterization to understand potential failure modes. FIAT predicted that it would take 84 seconds for the PICA to burn-through to the LI-900. The actual time to burn-through was observed to be 83 seconds. After burn-through, the test run continued for an additional 25 seconds, during which time the LI-900 slumped. The slumping was gradual, indicating that this failure mode occurs "gracefully."

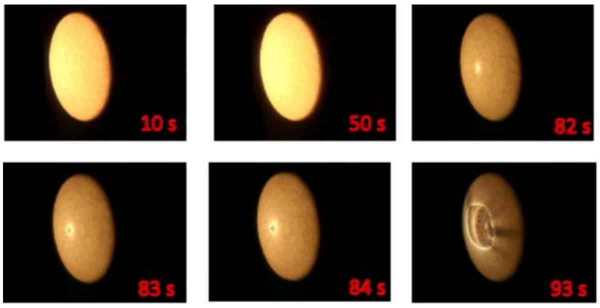

Fig. 6. Clips from a movie taken during the second heat pulse simulating entry from out-of-Mars orbit after aerocapture. The first pulse was simulated on this model by an earlier arc jet entry in the IHF facility as described in the text above.

Images of the face of the test article during the testing are shown for different times in Fig. 6. They were taken with a mirror at an oblique angle so the glowing model face appears elliptical in the figure. The front face of the model undergoes uniform recession from insertion until 82 seconds later. At 82 and 83 seconds, a brighter glowing is seen at the center of the model, at 83 seconds the PICA has been penetrated. At 84 seconds, the LI-900 region is exposed to the flow. As time progresses, the LI-900 slumps as shown in the clip taken at 93 seconds.

3. IN-DEPTH TEMPERATURE MEASUREMENTS AND ANALYSIS

As shown in Fig. 4, all models were instrumented with in-depth thermocouples (TCs). In addition to having axial TCs, there was a TC distribution embedded in the radial direction at the interface between the PICA and the LI-900. Predictions of the thermal response that would be recorded by the TCs were made with the FIAT analysis tool prior to the tests, using inputs appropriate to the materials stack-up. Figure 7 shows the measured temperatures along the axial dimensions as a function of time. The times for insertion and retraction of the model into the IHF stream are shown by the black vertical bars while the temporal profile of the TCs are color-coded. The profile for the TC closest to the surface, TC1, is shown in blue. The peak temperatures predicted by FIAT and measured values for TC1 are 1380 and 1400 ^{O}C, respectively. The comparison shows excellent correspondence between experiment and theory. After the model is removed from the arc jet stream the temperatures peak and then cool. As the time approaches 1050 seconds, TC1 is cooling faster than those TCs located deeper in the model. At 1050 seconds, TC1 is still cooling, and appears to be approaching the predicted cooled down temperature of 100 ^{O}C. The temporal profile for TC7, the deepest in the stack, was recording ~ 200 ^{O}C at the time of 1050 seconds, considerably higher than the prediction of 100 ^{O}C. It is remarkable that the 1D FIAT predictions for TC1 for the peak heating compare so well to the measured peak. It was suspected that the differences for all TCs at the late times are partially caused by 2D effects, i.e., sidewall heating of the PICA in the arc jet stream and the fact that PICA is heterogeneous with a higher in-plane thermal conductivity than that through the thickness. Milos and Chen [6] have analyzed such effects, specific to PICA only test articles with TITAN, a 2D code developed at NASA Ames.

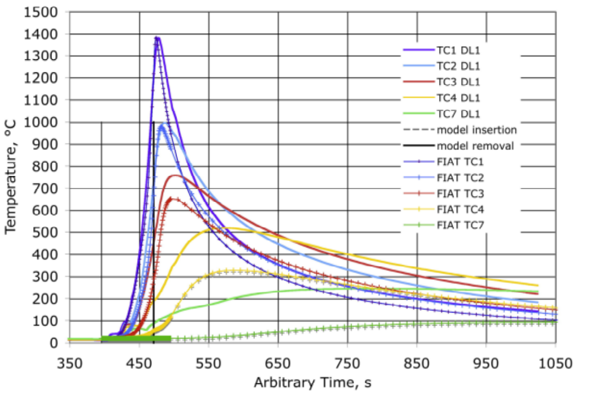

Fig. 7. Measured and predicted temperature profiles obtained from the 75 second run on a dual-layer model (DL1) at the IHF condition. The color coding depicts profliles from the axial TCs that were located at different depths from the front surface

To evaluate the 2D effects for the PICA atop LI-900 dual layer TPS, TITAN was run for the model geometry shown in Fig. 4.

Comparing the time when the peak TC temperature occurred with FIAT predictions, it is clear that FIAT under predicts this time and gets progressively worse with depth into model DL1, as shown in Fig. 7. The TITAN predictions of the time of peak temperature are much more accurate, as shown in Fig. 8. However, TITAN overpredicts peak temperature values for the first three TCs. This over prediction may be due to a two-dimensional modeling effect whereby an assumption of perfect contact between all surfaces was necessary. With the multiple contact surfaces associated with the model's construction (see Fig. 4), surface interference effects should not be ignored.

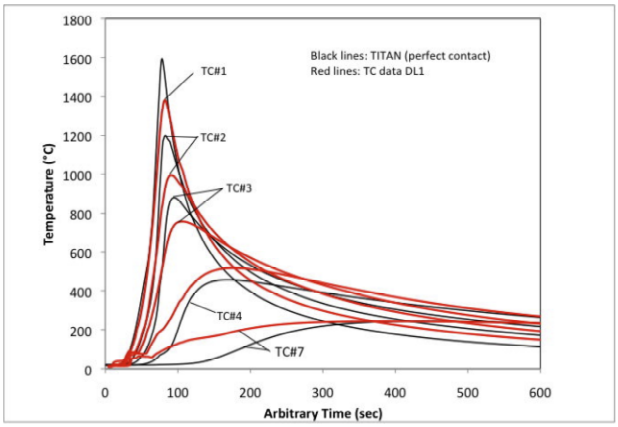

Fig. 8. Comparison of TITAN predictions with TC data from dual-layer model (DL1)

4.0 ANALYSIS OF CROSS-SECTIONED MODEL DL1 (INSERTED FOR 75 SECONDS AT THE IHF TEST CONDITION)

Prior to the sectioning of model DL1 (the model exposed to the IHF stream condition for 75 seconds), X-rays were taken and analyzed for cracking in the charred PICA. No discernible cracks were observed as shown in Fig. 9. Such cracking might be happen during cool-down of the model, but this did not occur.

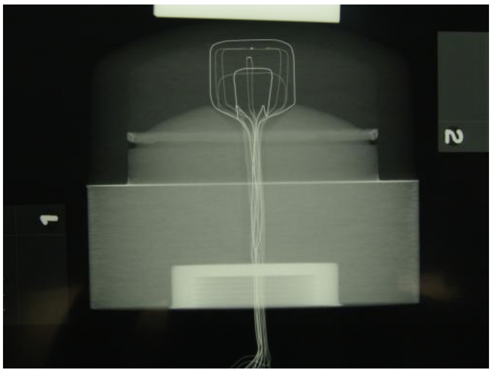

Fig. 9. X-ray photograph of model DL1 after IHF testing. As evident in the photograph, no cracking is evident throughout the model

Model (DL1) was then sectioned to help understand the thermophysics that occurred at the interface between the PICA and the LI-900. Fig. 10 is a photograph of the cross section with captions showing various features to be discussed below.

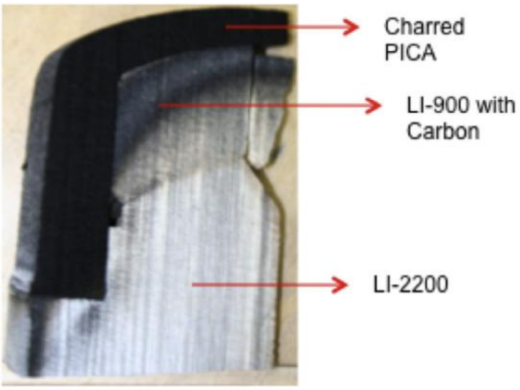

Fig. 10. Cross sectioned model DL1 that was exposed to the IHF stream condition for 75 seconds

As can be seen from Fig. 10, the ~ 0.61 cm of charred PICA on the front iso-Q face and down the sidewalls is jet black while the remaining 1.9 cm of LI-900 shows variable darkening. As confirmed by Energy Dispersive X-Ray (EDX) analysis discussed below, this darkening indicates there was flow-through of hot gases from the PICA exiting the side wall of the model. This is an artifact of the testing, not thought to be an issue for the 10 x 29 meter mid L/D heat shield design where such 2-D effects will not be important.

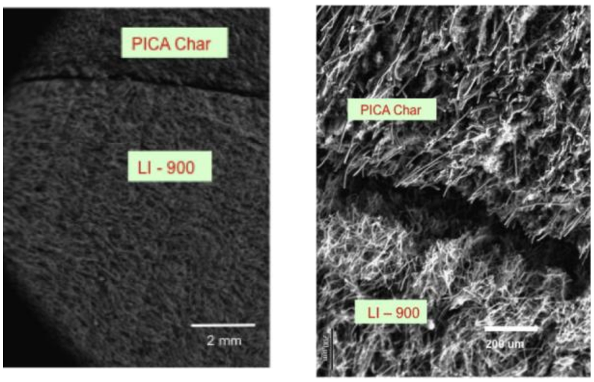

Fig. 11. SEM of the Cross sectioned model DL1 that was exposed to the IHF stream condition for 75 seconds

Fig. 11 is a scanning electron microscope (SEM) of the interface between the charred PICA and the LI-900 from model DL1 after being tested for 75 seconds at the IHF condition, and then cross-sectioned. The cut sections were carefully examined for microcracks and none were observed in either the PICA or the LI-900.

Figure 12 is a reproduction of EDX images obtained to provide information on the elemental composition of the PICA and LI-900 near the juncture of the two materials. The orientation of each compositional map is the same as shown in the upper left image with PICA char to the left, and LI-900 to the right. The map on the upper right of Fig. 12 shows high concentrations of carbon indicated by red, as expected for the PICA char. Not discernable in the top right reproduction, is a faint concentration of red in the LI-900 to the right, confirming that some hot pyrolysis gases containing carbon flowed through the LI-900 and left some residue in the tile material. The lower two images in Fig. 11, for oxygen and silicon, show high concentrations of these species as expected since LI-900 is essentially highly porous silica.

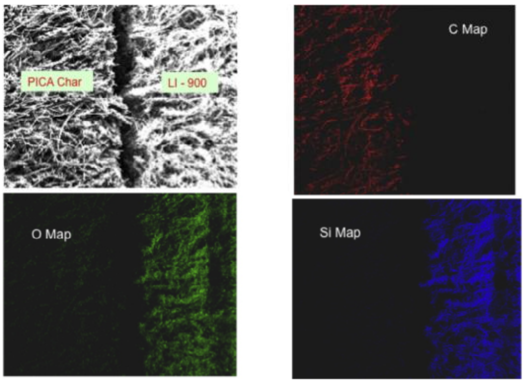

Fig. 12. EDX of the cross-sectioned model DL1 that was exposed to the IHF stream condition for 75 seconds.

5.0 SUMMARY AND CONCLUDING REMARKS

The work presented here clearly shows the viability of the thermal performance of the dual layer PICA atop LI-900, dual heat pulse concept for the human Mars mission. References 3 and 4 have shown viability of manufacturing a large-honeycomb TPS such as that for a 10 x 29 meter mid L/D (ellipsled). The pre-test simulations of the arc jet tests demonstrate that FIAT and TITAN predict the thermal performance of the PICA atop LI-900 quite well for the dual, constant heat pulse arc jet conditions that simulate the real dual heat pulse flight case. Predictions of recession and time for burn through for both the first and second heat pulses are accurate to within a second of those observed. **Importantly, charred PICA from the first pulse performed as predicted, and without defect during the second heat pulse.**

Further, as a part of the EDL-SA viability testing, four-point positive and negative flexural tests of PICA atop LI-900 in ~ 5 cm honeycomb showed encouraging results [7] for test articles bonded to an aluminum substrate.

It should be noted that the detailed analysis of the cross-sectioned model and the TITAN analysis were performed to understand aspects of the testing on the small arcjet models. For the 10 x 29 meter mid L/D vehicle such multi-dimensional effects will be minimal because the honeycomb will tend to eliminate hot gas flow-through and sidewall-heating effects will not be present.

Two issues remain to be resolved: (1) As shown in work by the Orion TPS ADP, PICA recession at heat rates below 50 W/cm^2 is not well predicted by FIAT because the surface thermochemical equilibrium assumption is usually not valid at lower surface temperatures. As with Orion, the low heating conditions will be experienced at the “tails” of the two flight heat pulses resulting in complications for the 10 x 29 meter heat shield designs. Such designs must retain some PICA atop the LI-900 to avoid the failure mode of slumping LI-900 caused from exposing the material to excessively hot shock layer gases on the substrate. (2) Fencing of the honeycomb at low heat fluxes may be an issue, requiring testing and refinement of the phenolic impregnated fiberglass honeycomb. The material used in this test series represents the first formulation of the new honeycomb technology [3,4].

6.0 RECOMMENDED FORWARD WORK

Additional arc jet and small-scale flight-testing of the honeycomb, dual layer PICA atop LI-900 TPS should be conducted over the range of conditions expected for the dual heat pulse, human Mars missions. Work should continue on the development of more advanced concepts for dual heat pulse, rigid TPS, and there should be TRL advancement of the large honeycomb technology since it shows great promise in being applicable to the manufacture of large heat shields without the gap issues that caused PICA to be dropped as the baseline TPS material for the Orion heat shield.

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

1. Drake, B. G., editor. *Human Exploration of Mars: Design Reference Architecture 5.0* s.l. : NASA-SP-2009-566, July 2009.
2. A.M.D. Ciancolo, et. al., Entry Descent and Landing Study: Phase 1 Report, NASA/TM-2010-000000000, April, 2010.
3. Peter T. Zell. Ethiraj Venkatapathy and James O. Arnold, (NASA Ames Research Center) *The Block-Ablator in a Honeycomb Heatshield Architecture,* International Planetary Probe Workshop, Barcelona Spain, June 12-18, 2010.
4. Congdon, W. M., (ARA Ablatives Laboratory) *Development of Design and Production Processes for a Block-Ablator Heatshield with Preliminary Test Results,* International Planetary Probe Workshop, Barcelona Spain, June 12-18, 2010.
5. Chen, Y.-K., and Milos, F.S., *Ablation and Thermal Response Program for Spacecraft Heatshield Analysis*, Journal of Spacecraft and Rockets, Vol. 36, No. 3, 1999, Pp. 475-483.
6. Chen, Y.-K., and Milos, F.S., "Two-Dimensional Implicit Thermal Response and Ablation Program for Charring Materials," Journal of Spacecraft and Rockets, Vol. 38, No. 4, 2001, pp. 473-481.
7. M. Blosser and C. Poteet, LaRC unpublished results.